

Luminosity Profiles of Resolved Young Massive Clusters

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Abstract. Young massive clusters differ markedly from old globular clusters in featuring extended, rather than tidally truncated, envelopes. Their projected-luminosity profiles are well fit by Elson-Fall-Freeman models with core radii $0.3 \text{ pc} \lesssim r_c \lesssim 8 \text{ pc}$ and *power-law envelopes* of negative exponent $2.0 \lesssim \gamma \lesssim 3.8$. These envelopes form within the first few 10^6 yr and last $\sim 10^8 - 10^{9.5} \text{ yr}$, depending on the environment. Many YMCs show clumpy substructure that may accelerate their initial relaxation. The cores of Magellanic-Cloud clusters show universal expansion from $r_c < 1 \text{ pc}$ at birth to $r_c = 2 - 3 \text{ pc}$ after 10^8 yr , but then seem to evolve along two bifurcating branches in a $r_c - \log(\text{age})$ diagram. The lower branch can be explained by mass-loss driven core expansion during the first 10^9 yr , followed by slow core contraction and the onset of core collapse due to evaporation. The upper branch, which shows continued core expansion proportional to logarithmic age, remains unexplained. There is strong evidence for rapid mass segregation in young clusters, yet little evidence for top-heavy IMFs or primordial mass segregation. Finally, YMCs show similar structure throughout the Local Group and as far away as we can resolve them ($\lesssim 20 \text{ Mpc}$).

1. Introduction

Luminosity profiles have long been used to study the structure and evolution of old globular clusters (e.g., King 1966; Illingworth & Illingworth 1976). Their application to the study of young massive clusters is of more recent origin, having begun in earnest with the classic study of ten rich, $8 - 300 \text{ Myr}$ old clusters in the LMC by Elson, Fall, & Freeman (1987, hereafter EFF87). As this study demonstrated, the luminosity profiles of YMCs differ significantly and systematically from those of old globulars. The observed differences contain important clues concerning the formation and dynamical evolution of massive star clusters.

Among the various motivations for studying luminosity profiles (hereafter LPs) of YMCs is our desire to understand the effects of mass segregation as a function of time and to separate any possible primordial mass segregation from the longer-term segregation caused by energy equipartition. Young massive clusters offer two main advantages: They still contain stars over most of the mass range of $\sim 0.1 - 120 M_\odot$, and they allow us to trace evolutionary effects directly as a function of cluster age.

Luminosity profiles can also yield information on core collapse, both slow and fast (“equipartition instability,” Spitzer 1969), and on the possible formation of central black holes in clusters. Finally, such profiles can help us evaluate the impact of mass loss on cluster formation and disruption, yielding estimates of the fraction of field stars that may have originated in clusters.

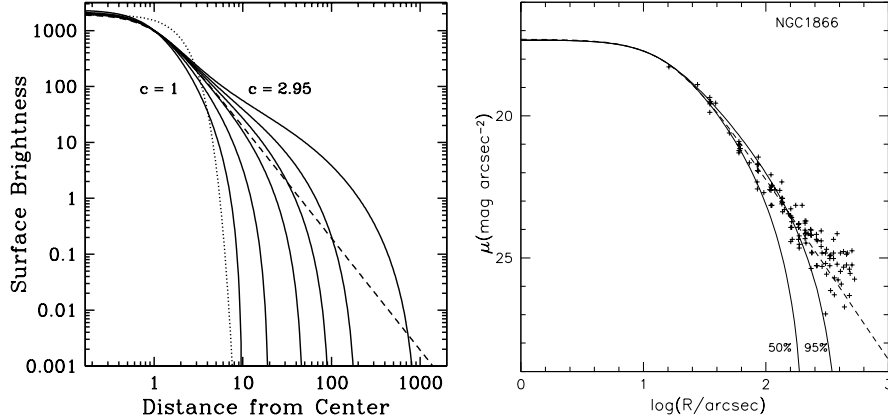


Figure 1. (a) (left) Family of King profiles (solid lines, $c = 1-2.95$) compared with Gaussian (dotted line) and modified Hubble profile (dashed, from Carlson & Holtzman 2001). King profiles fit old globular clusters well. (b) (right) Surface-brightness measurements for 130 Myr-old LMC cluster NGC 1866 (data points) compared with King profiles (solid curves) and best-fit EFF profile (dashed). The EFF profile fits the young-cluster profile with its power-law envelope best (from Lupton et al. 1989).

2. Luminosity Profiles: Basics

We are all familiar with King (1966) model profiles, shown in Fig. 1a, which fit the LPs of old globular clusters better than Gaussian or modified Hubble profiles do. King profiles are derived from model clusters with equal-mass stars and truncated Maxwellian velocity distributions (“lowered isothermal models”), and are characterized by three parameters: I_0 , r_c , and r_t (central surface brightness, core radius, and tidal radius). The concentration index, $c \equiv \log r_c/r_t$, is a measure of how strongly tidal truncation has affected the cluster.

As EFF87 first showed and Elson (1991) further demonstrated, young massive clusters in the LMC feature power-law envelopes and are well fit by model profiles of the form $I(r) = I_0(1 + r^2/a^2)^{-\gamma/2}$, much better so than by King profiles. At radii $r \gg a$, these EFF profiles take the simple power-law form $I(r) \sim r^{-\gamma}$. Like the King profiles, they are characterized by three parameters: I_0 , a , and γ (central surface brightness, characteristic radius, and power-law slope). The characteristic radius a is related to the core (= half-central-surface-brightness) radius r_c through $r_c = a(2^{2/\gamma} - 1)^{1/2}$. Figure 1b illustrates that the 130 Myr-old LMC cluster NGC 1866 is, indeed, better fit by an EFF model profile than by King profiles (EFF87; Lupton et al. 1989).

In trying to understand cluster dynamics, three characteristic time scales are important (e.g., Spitzer 1987; Meylan 2003): (1) the crossing time t_{cr} during which a star typically crosses the system; (2) the half-mass relaxation time t_{rh} during which stellar encounters redistribute energies to the point of setting up a near-Maxwellian velocity distribution within the half-mass radius; and (3) the evolution time t_{ev} , which is the time it takes for slow dynamical processes like the evaporation of stars from the cluster to significantly change the cluster size and profile. It has long been known that for globular clusters $t_{\text{cr}} \ll t_{\text{rh}} \ll t_{\text{ev}}$,

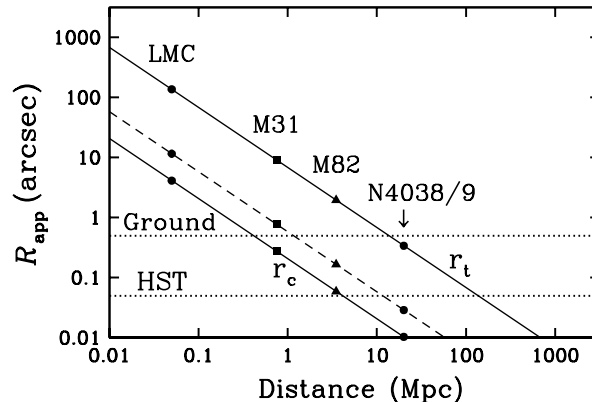


Figure 2. Apparent radii of a typical Milky-Way globular cluster at different hypothetical distances. Sloping lines mark the radii r_c , r_{eff} (*dashed*), and r_t .

with typical values of $t_{\text{cr}} \approx 10^6$ yr, $t_{\text{rh}} \approx 10^8$ yr, and $t_{\text{ev}} \approx 10^{10}$ yr. Thus, the LPs of young massive clusters should yield valuable information about equipartition and relaxation processes in the inner parts of these clusters.

How far can we hope to study LPs of clusters in sufficient detail to learn about the structural details that interest us? Figure 2 shows the *apparent* sizes of the core, half-light, and tidal radius of a typical Milky-Way globular cluster as a function of its hypothetical distance in Mpc. This typical globular, with radii taken as the median values of 143 globulars listed by Djorgovski (1993), has $r_c = 1.0$ pc, $r_{\text{eff}} = 2.8$ pc, and $r_t = 33$ pc, and a concentration index of $c = 1.53$. As the three sloping lines of Fig. 2 indicate, this cluster—if placed at the distance of the LMC—would show a fully resolved core even from the ground (assumed seeing of $0''.5$ FWHM). At the distance of M31 the same cluster would still appear well resolved with *HST*, while at the 3.5 Mpc distance of M82 its core would be only marginally resolved. Beyond the latter distance this typical cluster becomes unresolved at its center even when observed with *HST*. At the 20 Mpc distance of The Antennae galaxies, even the *half-light* radius of such a cluster can no longer be resolved with *HST* and has to be estimated by placing an upper limit on it. Because of these resolution limits, we first review the fully resolved LPs of young massive clusters within the Local Group and then the only partially resolved LPs of clusters beyond.

3. Young Massive Clusters in the Local Group

3.1. Magellanic Cloud Clusters

Much new information on LPs of YMCs in the Local Group has been published during the past five years, most of it for clusters in the Magellanic Clouds. Together the LMC and SMC host an estimated $\sim 6,000$ clusters, most of which are $\lesssim 3$ Gyr old, offering us a rich sample of YMCs in the $10^6 - 10^9$ yr age range. Mackey & Gilmore (2003a,b; hereafter MG03a,b) have just published the first systematic *HST*/WFPC2 study of LPs of 53 rich clusters in the LMC and 10

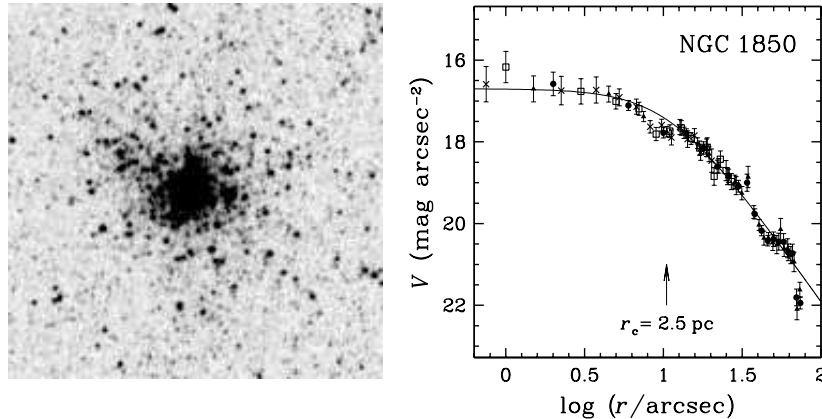


Figure 3. The 32 Myr-old LMC cluster NGC 1850 ($5' \times 5'$ field, NED/DSS) and its V -luminosity profile showing dips and bumps indicative of clumpy structure (from Mackey & Gilmore 2003a).

in the SMC, yielding profiles of sub-arcsecond resolution well into the cores ($1'' = 0.24$ pc at LMC distance). Some of their main results are as follows.

In general, virtually all observed profiles of clusters younger than 1 Gyr are well fit by EFF profiles, thus confirming the findings by EFF87. The slopes of the power-law envelopes lie in the range $\gamma = 2.0 - 3.8$, with a median $\gamma \approx 2.6$. Many profiles show bumps, steps, and/or wiggles, indicating the presence of significant substructure. As an example, Fig. 3 shows the 32 Myr old cluster NGC 1850 and its profile. Notice the inner dip at $r \approx 8''$ and the outer bump near $r = 60''$ ($\log r = 1.78$), which is created mainly by the distinct subclump of stars to the West, sometimes called NGC 1850 B. (The slope of the best-fit EFF profile shown in the figure is likely too shallow because of the limited extent of the WFPC2 data, and the fitted profile should probably go through the last group of data points.) Subclumps are seen in the envelopes of most very young clusters and can still be traced in some clusters several 100 Myr old, suggesting that cluster formation itself may be hierarchical (Kroupa 1998). Presumably, this clumpiness accelerates the initial relaxation of newborn clusters.

Interestingly, none of the observed 41 LMC clusters younger than 3 Gyr shows evidence of having undergone core collapse, as would be indicated by a profile with power-law shape at the very center (MG03a). However, such post-core-collapse (PCC) structure is found in 3 ± 1 of the 12 observed old ($\gtrsim 10$ Gyr) LMC globulars. These and a few other known PCC clusters have central power-law profiles of slope ≈ -0.7 and represent about $20\% \pm 7\%$ of the old cluster population in the LMC, a similar PCC fraction as is observed among the globulars of the Milky Way. These observations support the theoretical result that—at least for single-stellar-mass systems—core collapse takes $12 - 19 t_{\text{rh}}$ to occur, or about 300 central relaxation times (e.g., Binney & Tremaine 1987).

Correlations between the core radius and various other cluster parameters have been searched for, yet few have been found. Specifically, the core radius does not seem to correlate with cluster mass. The one significant correlation

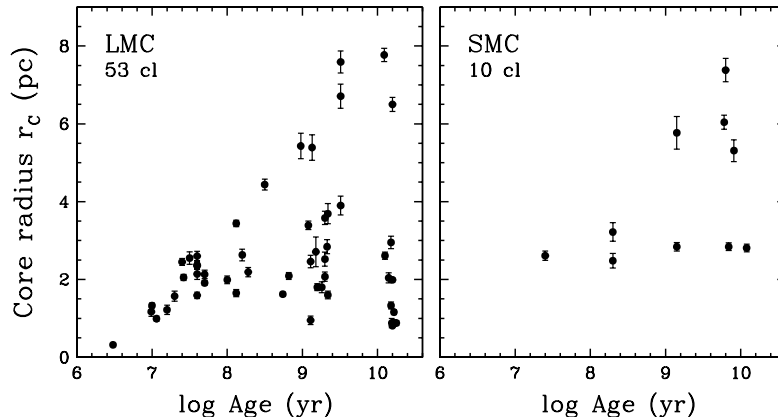


Figure 4. Core radii plotted vs. age for LMC and SMC clusters (MG03a,b).

found is between the core radius and cluster age, as first shown by Elson, Freeman, & Lauer (1989).

Trends of Core Radius with Age. Figure 4 shows the core radii of the 53 LMC and 10 SMC clusters observed by Mackey and Gilmore (MG03a,b) plotted versus cluster age τ . The new *HST* data confirm Elson et al's (1989) finding that the core radii of the youngest clusters are $\lesssim 1$ pc and show little scatter, while those of clusters older than 20 Myr tend to increase with age at least until $\tau \approx 1$ Gyr and show large scatter at $\tau \gtrsim 10$ Gyr ($0.8 \lesssim r_c \lesssim 8$ pc). However, the relation now appears to have *two branches*: a lower branch containing about 3/4 of the total cluster population and reaching a maximum *mean* core radius of ~ 2.5 pc at $\tau \approx 1-2$ Gyr before trending toward smaller r_c again, and an upper branch containing about 1/4 of the clusters and showing core radii that increase in proportion to the logarithmic age. As MG03a,b demonstrate, for clusters older than 10 Gyr as well as for all those older than 1 Gyr the bimodality in the core-radius distribution is highly significant ($>99\%$, $>99.5\%$), whence the bifurcation of the r_c -log τ relation into two branches appears real.

The time evolution of core radii traced by the *lower branch* is about as expected: The initial rapid core expansion is likely due to mass loss from massive stars ($\tau < 1$ Gyr), and is followed by slow core contraction due to continued energy equipartition and evaporation of stars, eventually leading to gravothermal instability and core collapse (Elson et al. 1989; see also Binney & Tremaine 1987).

The time evolution of core radii traced by the *upper branch*, however, remains unexplained. Clusters of similar age and metallicity on the upper and lower branches appear to have had very similar Initial Mass Functions (IMF) down to $\sim 0.8 M_\odot$, whence IMF variations can be ruled out as an explanation for the existence of two branches (de Grijs et al. 2002b). *N*-body simulations seem to also rule out as viable explanations any possible tidal-field variations due to different cluster orbits and hypothetical large variations in the primordial binary fraction (Wilkinson et al. 2003). Perhaps most promising is the very recent suggestion that core formation and expansion may be driven dynamically by the central accumulation of massive stars and their black-hole remnants (Merritt et

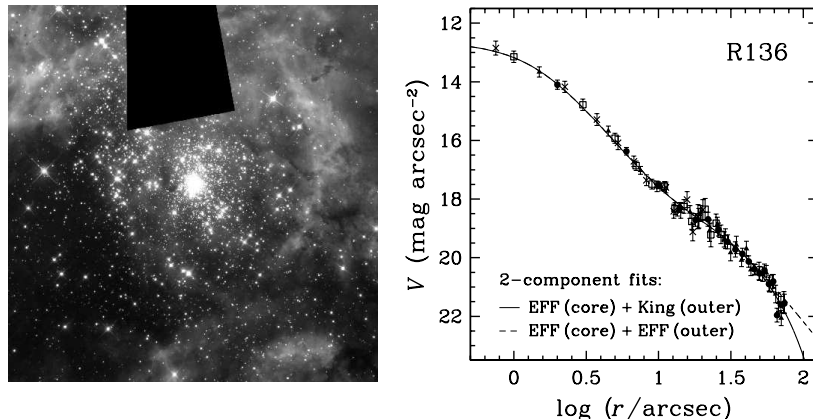


Figure 5. Newborn cluster R136/NGC 2070 ($115'' \times 115''$ field, NASA) and V-luminosity profile with two-component fits superposed (from MG03a).

al. 2004). The observed strong segregation of massive stars toward the cluster centers (e.g., de Grijs et al. 2002a) and simple model simulations that reproduce the approximately linear increase of r_c with logarithmic age both seem to support this hypothesis. Yet, the hypothesis does not explain why the scatter in core radii increases dramatically with age and why there should be two branches.

Newborn Cluster R136/NGC 2070. R136 is the high-surface-brightness core of the 3–4 Myr old cluster NGC 2070 located at the center of the 30 Doradus nebula, the most luminous HII region in the Local Group. Figure 5 shows the cluster and its luminosity profile. This profile is the only one among the 63 cluster profiles measured by MG03a,b that clearly shows a two-component structure. It is well fitted by a central EFF model profile with $r_c \lesssim 0.32$ pc ($1''.3$) within the core ($r \lesssim 10''$), and by a second EFF (or King) profile with $r_c \approx 3.7$ –8 pc ($15''$ – $33''$) beyond the core (Meylan 1993; MG03a).

Because R136/NGC 2070 is by far the youngest massive Magellanic Cloud cluster and possibly a globular cluster in formation (e.g., Kennicutt & Chu 1988), its study is of great interest and promises insights into the earliest dynamical evolution of YMCs. The evidence for mass segregation in it is strong: While the core radius is $r_c = 0.32$ pc for light from all stars, it drops to $r_c = 0.09$ pc for massive stars of $>20 M_\odot$ and ~ 0.03 pc for those of $>40 M_\odot$ (Brandl et al. 1996). It is this strong central concentration of the most massive and luminous stars that led, during the 1980s, to the mistaken belief that a supermassive star (“R136a”) of $\sim 2500 M_\odot$ might sit at the center of the cluster.

As we now know, there is a strong concentration of O3, O4, and WN stars at and near the center, some with masses thought to be as high as 130–150 M_\odot (Massey & Hunter 1998). Spectroscopy and IR observations of these and other, pre-main-sequence stars suggest that lower-mass stars began forming in NGC 2070 about 4–5 Myr ago, while the most massive stars formed a mere 1–2 Myr ago and quenched further star formation via their strong winds. Yet, despite this sequential formation the *overall* IMF of NGC 2070 appears to be essentially normal and Salpeter-like. Specifically, searches for low-mass stars

show evidence of rising numbers right into the core down to $\sim 2.8 M_{\odot}$ (Hunter et al. 1995) and even $0.6 M_{\odot}$ (Sirianni et al. 2000). Although because of the mass segregation the IMF does seem to flatten below $\sim 2 M_{\odot}$ within R136 itself, overall it appears very similar to the Kroupa (2001) or Chabrier (2003) IMFs now generally thought to be characteristic of star formation in the Milky-Way disk and in loose young clusters. Hence, the observations of this newborn cluster clearly contradict some theoretical predictions that the IMF of stars formed in high-density regions should be very top heavy. They also raise doubts about the importance of occasionally-claimed primordial mass segregation.

An interesting question is whether the unusual core-within-a-core structure of R136/NGC 2070 may have led to early core collapse. Spitzer (1969) showed that under certain circumstances clusters with a wide range of stellar masses may experience an *equipartition instability*, in which the most massive stars form a dense subsystem at the core of the lighter stars. While exchanging energy with the lighter stars, this subsystem can evolve away, rather than toward, equipartition, contracting rapidly and leading to accelerated core collapse. Whether this did or did not happen in R136 depends critically on the core radius measured as a function of mass and on the estimated central relaxation time. MG03a find marginal evidence for a central power-law cusp of slope -1.17 , but conclude—like Brandl et al. (1996) before—that the evidence favors strong and rapid dynamical mass segregation over any post-core-collapse state.

In short, the two-component profile of this $\sim 3\text{--}4$ Myr old cluster suggests that (i) strong dynamical evolution and mass segregation occur very early on and (ii) core growth during the first ~ 10 Myr may be complex.

3.2. Clusters in Other Local Group Galaxies

Surprisingly little information exists on the luminosity profiles of YMCs in Local Group galaxies other than the Magellanic Clouds. For the Milky Way, M31, and M33 the situation is as follows.

Milky-Way Clusters. The Milky Way seems to harbor few YMCs comparable to those in the LMC and SMC. Attempts to measure their LPs suffer from severe disk-star contamination and extinction. Perhaps the best studied is the $1\text{--}2$ Myr old cluster NGC 3603, whose $A_V = 4.5$ mag is relatively benign. It is one of the most massive young clusters known in the Milky Way, yet it has only about 1/40th the mass of R136/NGC 2070. Like the latter, it features low-mass stars of $0.1\text{--}1 M_{\odot}$ right into its center and has a normal IMF (e.g., Brandl et al. 1999). Infrared observations yield a LP with a core radius of $r_c = 0.78$ pc ($23''$) and extending out to at least 5 pc, where it becomes lost in the light of foreground stars (Nürnberg & Petr-Gotzens 2002). The situation is even more challenging for the Milky Way's central YMCs, with the Arches cluster showing extinction *variations* of $\Delta A_V \approx 10$ mag over $15''$ (Stolte et al. 2002) and, thus, offering little hope for any luminosity profiles in the near future.

M31 Clusters. Although some YMCs resembling young globulars have long been known to exist in M31 (e.g., van den Bergh 1969), none have had their LPs measured. Yet, at least for the four $60\text{--}160$ Myr old YMCs observed by Williams & Hodge (2001) with *HST*/WFPC2, LPs would be easy to derive from the archival images. Luminosity profiles have, however, been measured for *old*

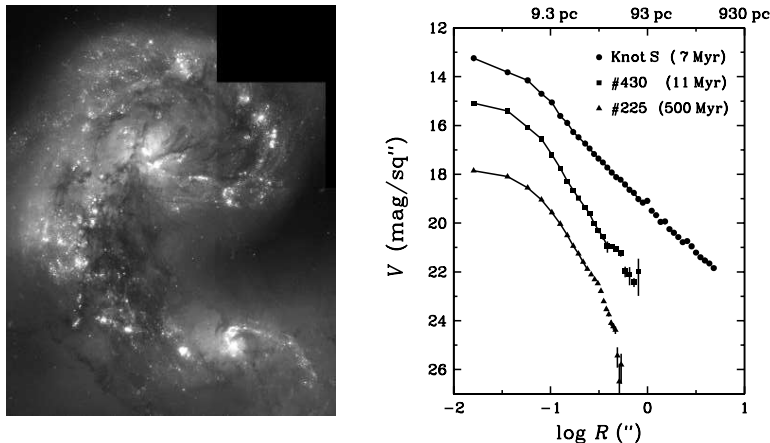


Figure 6. The Antennae galaxies (NGC 4038/39), and luminosity profiles of three young massive clusters in them (from Whitmore et al. 1999).

massive clusters and show evidence for PCC structure and extended envelopes (Grillmair et al. 1996) and, in the still controversial case of Cluster G1, for a central black hole of mass $2.0^{+1.4}_{-0.8} \times 10^4 M_{\odot}$ (Gebhardt, Rich, & Ho 2002).

M33 Clusters. M33 hosts a rich system of $10^6 - 10^{10}$ yr old clusters similar to those in the Magellanic Clouds. For ~ 60 of these clusters, LPs have been derived from *HST*/WFPC2 images and fitted with King profiles (Chandar, Bianchi, & Ford 1999). The measured core radii are $r_c \approx 0.2 - 2$ pc, and there is evidence for extended envelopes. At least for clusters younger than ~ 3 Gyr, the analysis needs to be repeated with the more appropriate EFF profiles.

4. Young Massive Clusters Beyond the Local Group

Even with *HST*, the cores of YMCs become marginally resolved around 2–4 Mpc and unresolved beyond (Fig. 2). Special software has been developed to analyze observations of partially resolved clusters by fitting King or EFF model light distributions (Larsen 1999; Carlson & Holtzman 2001). Therefore, we can still extract some size and shape parameters from YMCs out to at least 20 Mpc.

Among relatively nearby (2–6 Mpc) galaxies, luminosity profiles have been measured for YMCs in NGC 1569 (Hunter et al. 2000), M82 (de Grijs et al. 2001), and NGC 6946 (Larsen et al. 2001). In general, the core radii of these YMCs are similar to those measured in LMC clusters. Also, all YMCs younger than $\sim 10^8$ yr show power-law envelopes, and many show clumpy substructure.

An especially interesting case are the 43 globular clusters profiled in NGC 5128 (4 Mpc, Harris et al. 2002), where six of the most luminous clusters ($-10 \lesssim M_V \lesssim -11.3$) show envelopes extending beyond the best-fit King models. Although Harris et al. interpret these envelopes as being either due to evaporative mass loss or the remains of stripped former dwarf galaxies, a third possibility needs to be considered: The presence of intermediate-age globular clusters in NGC 5128 (Peng, Ford, & Freeman 2004) and the high luminosity

of the six globulars may indicate that these are relatively young clusters with incompletely stripped remains of their initial power-law envelopes.

Even for galaxies more distant than 10 Mpc, there is still much to learn from luminosity profiles of YMCs. Especially intriguing are the hints of dynamical evolution seen among clusters of different ages in The Antennae (Whitmore et al. 1999). Figure 6 shows the LPs of three massive clusters there: Knot S and #430 are both very young (7 and 11 Myr), have unresolved cores, and display pure power-law envelopes like young LMC clusters. In contrast, the 500 Myr-old Cluster #225 shows both a larger, partially resolved core ($r_c = 5.6$ pc) and an envelope with a distinct tidal cutoff. This suggests that, like elsewhere, young clusters in The Antennae form with power-law envelopes, but then get truncated over the next several 100 Myr by external tidal forces.

Finally, even at the 66 Mpc distance of the merger remnant NGC 7252 evidence for extended envelopes of YMCs can be found. Among the ~ 300 young halo globulars of solar metallicity and ages 300–600 Myr (Miller et al. 1997; Schweizer & Seitzer 1998), the five most luminous clusters feature extended envelopes reaching well past 100 pc radius. The most luminous, NGC 7252: W3 ($M_V = -16.2$), is a true supercluster with $r_{\text{eff}} = 17 \pm 2$ pc and a record-beating mass of $M = (8 \pm 2) \times 10^7 M_\odot$, corresponding to 15–20 \times the mass of ω Cen (Maraston et al. 2004). Apparently, while orbiting in the halo of NGC 7252 this heavy-weight young globular of age 300–500 Myr may have managed to hang on—so far—to most of its original power-law envelope.

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